

Observation of the $D_{sJ}^*(2317)$ and $D_{sJ}^*(2460)$ in B decays

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Abstract

We report on a study of the $B \rightarrow DD_{sJ}^*(2317)$ and $B \rightarrow DD_{sJ}^*(2460)$ decays based on 123.7×10^6 $B\bar{B}$ events collected with the Belle detector at KEKB. The $B \rightarrow DD_{sJ}^*(2317)$ and $B \rightarrow DD_{sJ}^*(2460)$ decays have been observed for the first time. We observe the $D_{sJ}^*(2317)$ decay to $D_s\pi^0$ and $D_{sJ}^*(2460)$ decay to the $D_s^*\pi^0$ and $D_s\gamma$ final states. We also set the 90% CL upper limits for the decays $D_{sJ}^*(2317) \rightarrow D_s^*\gamma$, $D_{sJ}^*(2460) \rightarrow D_s^*\gamma$, $D_{sJ}^*(2460) \rightarrow D_s\pi^0$ and $D_{sJ}^*(2460) \rightarrow D_s\pi^+\pi^-$.

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I. INTRODUCTION

Recently the BaBar collaboration reported on the observation of a new $D_s\pi^0$ resonance with a mass of 2317 MeV and a very narrow width [1]. A natural interpretation is that this is a p -wave $c\bar{s}$ quark state that is below the DK threshold, which accounts for the small width [2]. This interpretation is supported by the observation of a $D_s^*\pi^0$ resonance [3] by the CLEO collaboration [4]. Both groups observe these states in inclusive e^+e^- processes. The mass difference between the two observed states is consistent with the expected hyperfine splitting of the p -wave D_s meson doublet with total light-quark angular momentum $j = 1/2$ [2]. However, the masses of these states are considerably below potential model expectations [5], and are nearly the same as the corresponding $c\bar{u}$ states recently measured by Belle [6]. The low mass values have caused speculation that these states may be more exotic than a simple $q\bar{q}$ meson system [7, 8, 9, 10, 11, 12]. To clarify the nature of these states, it is necessary to determine their quantum numbers and decay branching fractions, particularly those for radiative decays. In this connection it is useful to search for these states, which we refer to as D_{sJ}^* , in exclusive B meson decay processes.

We search for decays of the type $B \rightarrow DD_{sJ}^*$, which are expected to be the dominant exclusive D_{sJ}^* production mechanism in B decays. Because of the known properties of the parent B meson, angular analyses of these decays could unambiguously determine the D_{sJ}^* quantum numbers. Moreover, since QCD sum rules in HQET predict that p -wave mesons with $j = 1/2$ should be more readily produced in B decays than mesons with $j = 3/2$ [13], the observation of $B \rightarrow DD_{sJ}^*$ would provide additional support for the p -wave nature of these states as well as serve as a check of these predictions.

In this Letter we report on a search for the $B \rightarrow DD_{sJ}^*(2317)$ and $B \rightarrow DD_{sJ}^*(2460)$ decays based on a 123.7×10^6 produced $B\bar{B}$ pairs at the KEKB asymmetric energy e^+e^- collider [15]. The inclusion of charge conjugate states is implicit throughout this report.

II. EVENT SELECTION

The Belle detector has been described elsewhere [14]. We select well measured charged tracks that have impact parameters with respect to interaction point (IP) that are less than 0.2 cm in the radial direction and less than 2.5 cm along the beam direction (z). We also require that the transverse momentum of the tracks be greater than 0.05 GeV/ c in order to reduce the combinatorial background from low momentum particles.

For charged particle identification (PID), the combined information from specific ionization in the central drift chamber (dE/dx), time-of-flight scintillation counters and aerogel Čerenkov counters is used. Charged kaons are selected with PID criteria that have an efficiency of 88%, a pion misidentification probability of 8%, and negligible contamination from protons. All charged tracks with PID responses consistent with a pion hypothesis that are not positively identified as electrons are considered as pion candidates.

Neutral kaons are reconstructed via the decay $K_S^0 \rightarrow \pi^+\pi^-$ with no PID requirements for the daughter pions. The two-pion invariant mass is required to be within 9 MeV/ c^2 ($\sim 3\sigma$) of the K^0 mass and the displacement of the $\pi^+\pi^-$ vertex from the IP in the transverse ($r - \phi$) plane is required to be between 0.2 cm and 20 cm. The direction in the $r - \phi$ plane from the IP to the $\pi^+\pi^-$ vertex is required to agree within 0.2 radians with the combined momentum of the two pions.

Photon candidates are selected from energy deposit clusters in the CsI electromagnetic

calorimeter. Each photon candidate is required to have a laboratory energy greater than 30 MeV with no associated charged track, and a shower shape that is consistent with an electromagnetic shower. A pair of photons with an invariant mass within 12 MeV/ c^2 ($\sim 2.5\sigma$) of the π^0 mass is considered as a π^0 candidate.

We reconstruct D_s^+ mesons in the $\phi\pi^+$, $\bar{K}^{*0}K^+$ and $K_S^0K^+$ decay channels. The ϕ mesons are reconstructed from the K^+K^- pairs with the invariant mass within 10 MeV/ c^2 ($\sim 2.5\Gamma$) from the ϕ mass. The \bar{K}^{*0} mesons are reconstructed from $K^-\pi^+$ pairs with an invariant mass within 75 MeV/ c^2 (1.5Γ) of the \bar{K}^{*0} mass. After calculating the invariant mass of the corresponding set of particles, we define a D_s signal region as being within 12 MeV/ c^2 ($\sim 2.5\sigma$) of the D_s mass. D_s^* mesons are reconstructed in the $D_s^* \rightarrow D_s\gamma$ decay channel. The mass difference between D_s^* and D_s candidates is required to be within 8 MeV/ c^2 of its nominal value ($\sim 2.5\sigma$).

We reconstruct $\bar{D}^0(D^-)$ mesons in the $K^+\pi^-$, $K^+\pi^-\pi^-\pi^+$ and $K^+\pi^-\pi^0$ ($K^+\pi^-\pi^-$) decay channels and require the invariant mass to be within 12 MeV/ c^2 of the $\bar{D}^0(D^-)$ mass. For the π^0 from the $\bar{D}^0 \rightarrow K^+\pi^-\pi^0$ decay, we require that the π^0 momentum in the $\Upsilon(4S)$ center-of-mass (CM) frame be greater than 0.4 GeV/ c in order to reduce combinatorial backgrounds.

We combine D candidates with a $D_s^{(*)+}$ and a π^0 , γ , or $\pi^+\pi^-$ pair to form B mesons. Candidate events are identified by their CM energy difference, $\Delta E = (\sum_i E_i) - E_b$, and the beam constrained mass, $M_{bc} = \sqrt{E_b^2 - (\sum_i \vec{p}_i)^2}$, where E_b is the beam energy and \vec{p}_i and E_i are the momenta and energies of the decay products of the B meson in the CM frame. We select events with $M_{bc} > 5.2$ GeV/ c^2 and $|\Delta E| < 0.2$ GeV, and define a B signal region of 5.272 GeV/ $c^2 < M_{bc} < 5.288$ GeV/ c^2 and $|\Delta E| < 0.03$ GeV. In the cases with more than one candidate in an event, the one with the D and $D_s^{(*)+}$ masses closest to the nominal values is chosen. We use a Monte Carlo (MC) simulation to model the response of the detector and determine the efficiency [16].

III. BACKGROUND SUPPRESSION

Variables that characterize the event topology are used to suppress background from the two-jet-like $e^+e^- \rightarrow q\bar{q}$ continuum process. We require $|\cos\theta_{\text{thr}}| < 0.80$, where θ_{thr} is the angle between the thrust axis of the B candidate and that of the rest of the event; this eliminates 77% of the continuum background while retaining 78% of the signal events. To suppress combinatorial background we apply a restriction on the invariant mass of the D meson and the π^0 or γ from D_{sJ}^* decay: $M(D\pi^0) > 2.3$ GeV/ c^2 , $M(D\gamma) > 2.2$ GeV/ c^2 .

IV. RESULTS OF THE ANALYSIS

A. Calculation of branching fractions

The ΔE and D_{sJ}^* candidate's invariant mass ($M(D_{sJ}^*)$) distributions for $B \rightarrow DD_{sJ}^*$ candidates are presented in Fig. 1, where all \bar{D}^0 and D^- decay modes are combined. Each distribution is the projection of the signal region of the other parameter; distributions for events in the $M(D_{sJ}^*)$ and ΔE sidebands are shown as hatched histograms.

Clear signals are observed for the $DD_{sJ}^*(2320)[D_s\pi^0]$ and $DD_{sJ}^*(2460)[D_s^*\pi^0, D_s\gamma]$ final states. The measured masses for the $D_{sJ}^*(2317)$ and $D_{sJ}^*(2460)$ are $(2319.8 \pm 2.1 \pm 2.0)$ MeV/ c^2

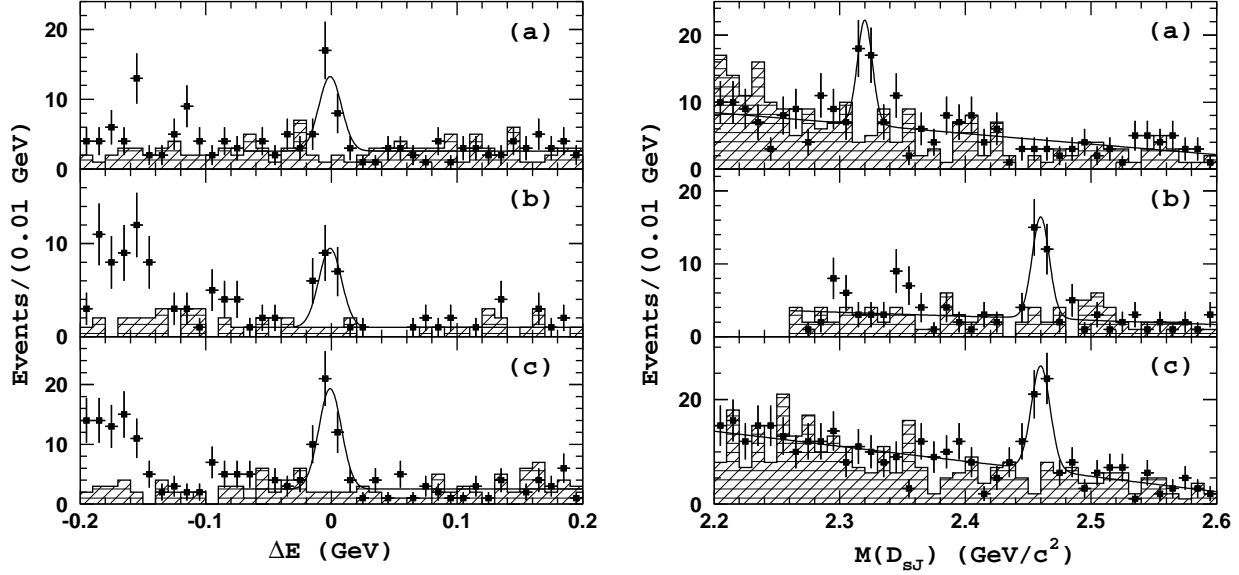


FIG. 1: ΔE (left) and $M(D_{sJ}^*)$ (right) distributions for the $B \rightarrow DD_{sJ}^*$ candidates: (a) $D_{sJ}^*(2320) \rightarrow D_s \pi^0$, (b) $D_{sJ}^*(2460) \rightarrow D_s^* \pi^0$ and (c) $D_{sJ}^*(2460) \rightarrow D_s \gamma$. Points with errors represent the experimental data, hatched histograms show the sidebands and curves are the results of the fits.

and $(2459.2 \pm 1.6 \pm 2.0) \text{ MeV}/c^2$.

For each decay channel, the ΔE distribution is fitted with a Gaussian signal and a linear background function. The Gaussian mean value and width are fixed to the values from a MC simulation of signal events. The region $\Delta E < -0.07 \text{ GeV}$ is excluded from the fit to avoid contributions from other B decays of the type $B \rightarrow DD_{sJ}^* X$ where X denotes an additional particle that is not reconstructed. The fit results are given in Table I, where the listed efficiencies include intermediate branching fractions. The statistical significance of the signal quoted in Table I is defined as $\sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_{max})}$, where \mathcal{L}_{max} and \mathcal{L}_0 denote the maximum likelihood with the nominal and with zero signal yield, respectively.

The combined fit quoted in Table II is the summed results for the \bar{D}^0 and D^- modes assuming isospin invariance. The normalization of the background in each sub-mode is allowed to float while the signal yields are required to satisfy the constraint $N_i = N_{B\bar{B}} \cdot \mathcal{B}(B \rightarrow DD_{sJ}^*) \cdot \varepsilon_i$, where the branching fraction $\mathcal{B}(B \rightarrow DD_{sJ}^*)$ is a fit parameter; $N_{B\bar{B}}$ is the number of $B\bar{B}$ pairs and ε_i is the efficiency, which includes all intermediate branching fractions. From the two $B \rightarrow DD_{sJ}^*(2460)$ branching fraction measurements, we determine the ratio $\mathcal{B}(D_{sJ}^*(2460) \rightarrow D_s \gamma) / \mathcal{B}(D_{sJ}^*(2460) \rightarrow D_s^* \pi^0) = 0.38 \pm 0.11 \pm 0.04$.

The signals for the $B \rightarrow DD_{sJ}^*(2317)[D_s \pi^0]$ and $B \rightarrow DD_{sJ}^*(2460)[D_s^* \pi^0, D_s \gamma]$ channels have greater than 5σ statistical significance. Figure 2 shows the ΔE distributions for the other channels, where significant signals are not seen. We set 90% confidence level (CL) upper limits for these modes based on an event yield N that is calculated from the relation $\int_0^N \mathcal{L}(n) dn = 0.9 \int_0^\infty \mathcal{L}(n) dn$, where $\mathcal{L}(n)$ is the maximum likelihood with the signal yield equal to n .

TABLE I: Branching fractions $B \rightarrow DD_{sJ}^*$ decays.

Decay channel	ΔE yield	$M(D_{sJ}^*)$ yield	Efficiency, 10^{-4}	\mathcal{B} , 10^{-4}	Significance
$B^+ \rightarrow \bar{D}^0 D_{sJ}^{*+}(2317) [D_s^+ \pi^0]$,	$13.7^{+5.1}_{-4.5}$	$13.4^{+6.2}_{-5.4}$	1.36	$8.1^{+3.0}_{-2.7} \pm 2.4$	5.0σ
$B^0 \rightarrow D^- D_{sJ}^{*+}(2317) [D_s^+ \pi^0]$	$10.3^{+3.9}_{-3.1}$	$10.8^{+4.2}_{-3.6}$	0.97	$8.6^{+3.3}_{-2.6} \pm 2.6$	6.1σ
$B^+ \rightarrow \bar{D}^0 D_{sJ}^{*+}(2317) [D_s^{*+} \gamma]$	$3.4^{+2.8}_{-2.2}$	$2.1^{+4.1}_{-3.4}$	1.15	$2.4^{+2.0}_{-1.5} (< 5.7)$	—
$B^0 \rightarrow D^- D_{sJ}^{*+}(2317) [D_s^{*+} \gamma]$	$2.3^{+2.5}_{-1.9}$	$1.6^{+2.4}_{-1.9}$	0.71	$2.6^{+2.8}_{-2.2} (< 7.1)$	—
$B^+ \rightarrow \bar{D}^0 D_{sJ}^{*+}(2460) [D_s^{*+} \pi^0]$	$7.2^{+3.7}_{-3.0}$	$8.9^{+4.0}_{-3.3}$	0.49	$11.9^{+6.1}_{-4.9} \pm 3.6$	2.9σ
$B^0 \rightarrow D^- D_{sJ}^{*+}(2460) [D_s^{*+} \pi^0]$	$11.8^{+3.8}_{-3.2}$	$14.9^{+4.4}_{-3.9}$	0.42	$22.7^{+7.3}_{-6.2} \pm 6.8$	6.5σ
$B^+ \rightarrow \bar{D}^0 D_{sJ}^{*+}(2460) [D_s^+ \gamma]$	$19.1^{+5.6}_{-5.0}$	$20.2^{+7.2}_{-6.9}$	2.75	$5.6^{+1.6}_{-1.5} \pm 1.7$	5.0σ
$B^0 \rightarrow D^- D_{sJ}^{*+}(2460) [D_s^+ \gamma]$	$18.5^{+5.0}_{-4.3}$	$19.6^{+5.6}_{-4.9}$	1.83	$8.2^{+2.2}_{-1.9} \pm 2.5$	6.5σ
$B^+ \rightarrow \bar{D}^0 D_{sJ}^{*+}(2460) [D_s^{*+} \gamma]$	$4.4^{+3.8}_{-3.3}$	$8.2^{+4.0}_{-3.4}$	1.15	$3.1^{+2.7}_{-2.3} (< 7.5)$	—
$B^0 \rightarrow D^- D_{sJ}^{*+}(2460) [D_s^{*+} \gamma]$	$1.1^{+1.8}_{-1.2}$	$0.2^{+1.8}_{-1.2}$	0.71	$1.3^{+2.0}_{-1.4} (< 4.6)$	—
$B^+ \rightarrow \bar{D}^0 D_{sJ}^{*+}(2460) [D_s^+ \pi^+ \pi^-]$	< 4.0	$-2.2^{+2.0}_{-1.6}$	1.89	< 1.7	—
$B^0 \rightarrow D^- D_{sJ}^{*+}(2460) [D_s^+ \pi^+ \pi^-]$	< 2.5	$-1.2^{+2.7}_{-2.0}$	1.35	< 1.5	—
$B^+ \rightarrow \bar{D}^0 D_{sJ}^{*+}(2460) [D_s^+ \pi^0]$	< 2.4	$1.0^{+2.7}_{-2.0}$	0.94	< 2.1	—
$B^0 \rightarrow D^- D_{sJ}^{*+}(2460) [D_s^+ \pi^0]$	< 2.4	$0.3^{+1.8}_{-1.2}$	0.68	< 2.8	—

TABLE II: Combined fit results.

Decay channel	\mathcal{B} , 10^{-4}	Significance
$B \rightarrow DD_{sJ}^*(2317) [D_s \pi^0]$	$8.5^{+2.1}_{-1.9} \pm 2.6$	6.1σ
$B \rightarrow DD_{sJ}^*(2317) [D_s^* \gamma]$	$2.5^{+2.0}_{-1.8} (< 5.8)$	1.8σ
$B \rightarrow DD_{sJ}^*(2460) [D_s \pi^0]$	$17.8^{+4.5}_{-3.9} \pm 5.3$	6.4σ
$B \rightarrow DD_{sJ}^*(2460) [D_s \gamma]$	$6.7^{+1.3}_{-1.2} \pm 2.0$	7.4σ
$B \rightarrow DD_{sJ}^*(2460) [D_s^* \gamma]$	$2.7^{+1.8}_{-1.5} (< 5.6)$	2.1σ
$B \rightarrow DD_{sJ}^*(2460) [D_s \pi^+ \pi^-]$	< 1.2	—
$B \rightarrow DD_{sJ}^*(2460) [D_s \pi^0]$	< 1.4	—

B. Angular analysis

The helicity angle analysis can provide information about spin of the decaying particle. We study the helicity angle distribution for the $D_{sJ}^*(2460) \rightarrow D_s \gamma$ decay.

The helicity angle $\theta_{D_s \gamma}$ is defined as the angle between the $D_{sJ}^*(2460)$ momentum in the B meson rest frame and the D_s momentum in the $D_{sJ}^*(2460)$ rest frame. The distribution shown in Fig. 3 is consistent with MC expectations for a $J = 1$ hypothesis for the $D_{sJ}^*(2460)$ ($\chi^2/\text{n.d.f} = 5/6$), and contradicts the $J = 2$ hypothesis ($\chi^2/\text{n.d.f} = 44/6$).

C. Cross checks & systematic uncertainties

We study the possible feed-across between all studied D_{sJ}^* decay modes using MC. We also analyse a MC sample of generic $B\bar{B}$ events corresponding to our data sample. No

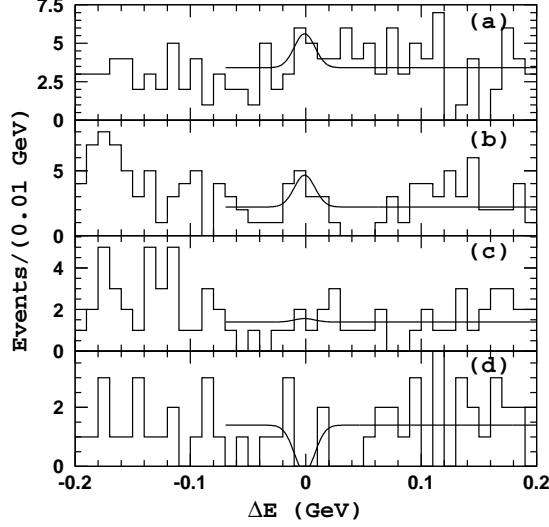


FIG. 2: ΔE distributions for the decay channels with not significant signals: (a) $DD_{sJ}^*(2320)[D_s^*\gamma]$, (b) $DD_{sJ}^*(2460)[D_s^*\gamma]$, (c) $DD_{sJ}^*(2460)[D_s\pi^+\pi^-]$, (d) $DD_{sJ}^*(2460)[D_s\pi^0]$. Open histograms represent the experimental data and curves show the results of the fits.

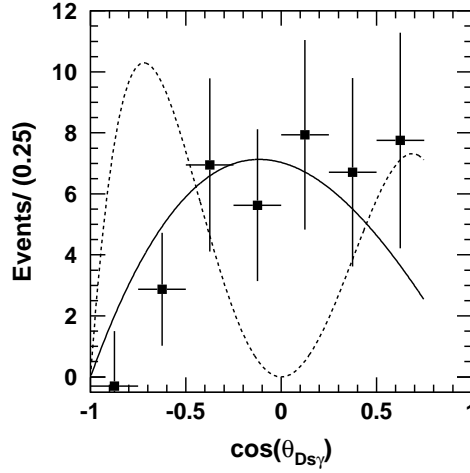


FIG. 3: The $D_{sJ}^*(2460) \rightarrow D_s\gamma$ helicity distribution. The points with error bars are the results of fits to the ΔE spectra for experimental events in the corresponding bin. Solid and dashed curves are MC predictions for a $J = 1$ and $J = 2$ hypothesis, respectively. The highest bin has no events because of cut to the $D\gamma$ invariant mass.

peaking background is found.

As a check, we apply a similar procedure to decay chains with the same final states: $B \rightarrow DD_s^*$, $B \rightarrow D^*D_s$ and $B \rightarrow D^*D_s^*$. For each mode, we measure branching fractions that are consistent with the world average values [17].

The following sources of systematic errors are considered: tracking efficiency (1-2% per track), kaon identification efficiency (1%), π^0 efficiency (6%), K_S^0 reconstruction efficiency (6%), efficiency for slow pions from $D^* \rightarrow D\pi$ decays (8%), D branching fraction uncer-

tainties (2%-6%), signal and background shape parameterization (4%) and MC statistics (3%). The uncertainty in the tracking efficiency is estimated using partially reconstructed $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K_S^0\pi^+\pi^-$ decays. The kaon identification uncertainty is determined from $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$ decays. The π^0 reconstruction uncertainty is obtained using \bar{D}^0 decays to $K^+\pi^-$ and $K^+\pi^-\pi^0$. We assume equal production rates for B^+B^- and $B^0\bar{B}^0$ pairs and do not include the uncertainty related to this assumption in the total systematic error. For the calculation of the branching fractions, the errors in the D_s meson branching fractions are taken into account. These uncertainties are dominated by the error of the $D_s \rightarrow \phi\pi^+$ branching ratio of 25% [17]. The overall systematic uncertainty is 30%.

V. CONCLUSION

In summary, we report the first observation of $B \rightarrow DD_{sJ}^*(2320)$ and $B \rightarrow DD_{sJ}^*(2460)$ decays. The measured branching fractions with the corresponding statistical significances are presented in Table II. The angular analysis of the $D_{sJ}^*(2460) \rightarrow D_s\gamma$ decay supports the hypothesis that $D_{sJ}^*(2460)$ is a 1^+ state.

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